Fuel classification and mapping from satellite imagines

TIAN Xiao-rui[1], Douglas J. McRae[2], SHU Li-fu[1], WANG Ming-yu[1]

[1] Research Institute of Forestry Protection, Chinese Academy of Forestry. Beijing 100091, P. R. China;

[2] Natural Resources Canada, Canadian Forest Service, 1219 Queen St. E. Sault Ste. Marie, Ontario P6A 2E5, Canada

Abstract: This paper summarizes the fuel type systems currently adopted by the fire danger rating systems or fire behavior prediction systems of some countries, such as Canada, the United States, Australia, Greece, and Switzerland. As an example, the Canadian Forest Fire Danger Rating System organizes fuel types into five major groups, with a total of 16 discrete fuel types recognized. In the United States National Fire Danger Rating System, fuel models are divided into four vegetation groups and twenty fire behavior fuel models. The Promethus System (Greece) divides fuels into 7 types, and Australia has adopted only three distinct fuel types: open grasslands, dry eucalyptus forests, and heath/shrublands. Four approaches to mapping fuels are acceptable: field reconnaissance, direct mapping methods, indirect mapping methods, and gradient modeling. Satellite remote-sensing techniques provide an alternative source of obtaining fuel data quickly, since they provide comprehensive spatial coverage and enough temporal resolution to update fuel maps in a more efficient and timely manner than traditional aerial photography or fieldwork. Satellite sensors can also provide digital information that can be easily tied into other spatial databases using Geographic Information System (GIS) analysis, which can be used as input in fire behavior and growth models. Various fuel-mapping methods from satellite remote sensing are discussed in the paper. According to the analysis of the fuel mapping techniques worldwide, this paper suggests that China should first create appropriate fuel types for its fire agencies before embarking on developing a national fire danger rating system to improve the current data situation for it's fire management programs.

Keywords Fire behavior; Fire danger; Fuel type classification; Fuel mapping; Fuel model.

CLC number: S762.31: TB871　　　　　　**Document code:** A　　　　**Article ID:** 1007-662X(2005)04-0311-06

Introduction

In recent years, wildland fires have become a more serious threat resulting in increased loss of life and resource damage, which is unacceptable nowadays. Critical to resolving this problem is better information on the amount and conditions of natural fuels on wildland areas.

Fuel typing is the basic concept for describing the status of a particular fuel. Often it is used in conjunction with a country's forest fire danger rating systems as the primary input of fire behavior models. A fuel type is an identifiable association of fuel elements of distinctive species, form, size, arrangement, or other characteristics that will cause a predictable rate of spread or resistance to control under specified weather conditions (Food and Agriculture Organization of the United Nations 1986; National Wildfire Coordinating Group 1996; Canadian Interagency Forest Fire Centre 2002). Specifically, a fuel type is a fuel complex of sufficient homogeneity and extending over an area of sufficient size that its equilibrium fire behavior can be maintained (Forestry Canada Fire Danger Group 1992). The term "fuel model" means the simulated fuel complex for which all fuel descriptors required for the solution of a mathematical rate-of-spread model have been specified (Food and Agriculture Organization of the United Nations 1986; National Wildfire Coordinating Group 1996).

Fuel type, as well as topography and microclimatic conditions,

are some of the most important factors that should be taken into consideration for fire planning (Keane 2001). Fuel classification is a mapping technique developed by different fire management organizations that adopt not only the topographical and geographical characteristics of the area being analyzed, but also takes into account specific local climatic conditions and the prevalent human activities in the area that might affect the fuel load (Trabaud, 1999). This is why fuel mapping is an extremely difficult and complex process requiring expertise in remote-sensing image classification, fire behavior, fuel modeling, ecology, and Geographical Information Systems (GIS) analysis. A problem that remains unsolved is that an adequate classification method has still not been developed, which can provide satisfactory results to all users. Most of the techniques used in the past have employed aerial photography or satellite imagery, which use different spectral information. The aim of this paper is to summarize the fuel-type systems and to discuss the fuel mapping methods currently used in the world followed by some suggestions on the need for developing a fuel type system for China.

Main fuel classification in the world

Fuel types in Canadian Forest Fire Danger Rating System

The current form of the Canadian Forest Fire Danger Rating System (CFFDRS) is made up of two major subsystems that have been formally documented and disseminated. The two major CFFDRS subsystems, the Canadian Forest Fire Weather Index (FWI) System (Canadian Forest Service 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) have been used operationally throughout all of Canada for a number of years. These systems are national and can be used anywhere throughout Canada. The FBP System organizes fuels into five major groups (e.g., coniferous, deciduous, mixedwood, slash, and open), with a total of 16 discrete fuel types altogether recognized (Forestry Canada

Fire Danger Group 1992). These fuel types are used to describe fire behavior characteristics that would be expected under various burning conditions. Fire behavior models for spread rate and fuel consumption in the FBP System were derived from a database of over 400 experimental, wild, and prescribed fire observations. The FBP System is based on simple mathematical models, and they are partly based on physical and experimental models. Fuel types in the FBP System are described qualitatively, rather than quantitatively, using descriptive terms on stand structure and composition, surface and ladder fuels, and the specific forest floor cover and organic (duff) layer present. The major fuel types of FBP System are briefly summarized in Table 1.

Table 1. Fuel types of the Canadian FBP System.

Group/Identifier	Descriptive name
Coniferous	C-1: Spruce-lichen woodland
	C-2: Boreal spruce
	C-3: Mature jack or lodgepole pine
	C-4: Immature jack or lodgepole pine
	C-5: Red and white pine
	C-6: Conifer plantation
	C-7: Ponderosa pine-Douglas-fir
Deciduous	D-1: Leafless aspen
Mixedwood	M-1: Boreal mixedwood-leafless
	M-2: Boreal mixedwood-green
	M-3: Dead balsam fir mixedwood-leafless
	M-4: Dead balsam fir mixedwood-green
Slash	S-1: Jack or lodgepole pine slash
	S-2: White spruce-balsam slash
	S-3: Coastal cedar-hemlock-Douglas-fir slash
Open	O-1: Grass

Fuel models in National Fire Danger Rating System (NFDRS) of the United States

NFDRS was released for general use by agencies throughout the United States in 1972 with modified versions released in 1978 and 1988 (Andrews *et al.* 2003). The current system is based on physics of combustion- and laboratory-developed constants and coefficients reflecting the relationships between various fuels, weather, topography, and risk conditions, which is different from the field-collected data of the Canadian System.

In NFDRS, a fuel model is a set of fuel particle and fuel bed descriptors required as inputs to run Rothermel fire spread model (Rothermel 1972). Fuel models are divided into four vegetation groups that account for fuels composed mainly of grass, shrub, timber, and slash. In the NFDRS these four vegetation types are further subdivided into 20 distinct fuel models. The 13 fire behavior fuel models are crossreferenced to the 20 fuel models of the NFDRS by means of a similarity chart, which are presented in 4 fuel groups: grasslands, shrublands, timber, and slash. Each group comprises three or more fuel models. (Anderson 1982). Table 2 gives the physical description similarity chart of NFDRS and Fire behavior fuel models. These models are used to run Rothermel's (1972) fire spread model and include only descriptors of fine fuels that burn in fire front. The fuel models shown in Table 2 were alined according to the fuel layer controlling the rate of fire spread. Some second and third choices are indicated for situations where fire spread may be governed by two or more fuel layers, depending on distribution and moisture content. A criterion for choosing a specific fuel model is that the model represents the best conditions of fire burns in the fuel stratum. This means that there will be situations where one fuel model better represents rate of spread while another fuel model may better depict fireline intensity (Byram 1959).

Table 2. National Fire Danger Rating System (NFDRS) and Fire Behavior Prediction System (FBPS) fuel models

NFDRS fuel models (A–U).....FIRE BEHAVIOR fuel models (# 1–13)

[NFDRS models realined to fuels controlling spread under severe burning conditions]

NFDRS fuel models	BEHAVE fire behavior fuel models												
	1	2	3	4	5	6	7	8	9	10	11	12	13
A – Western annuals	×	-	-	-	-	-	-	-	-	-	-	-	-
L - Western perennial	×	-	-	-	-	-	-	-	-	-	-	-	-
S –Tundra	×	-	-	-	-	3rd	-	-	2nd	-	-	-	-
C - Open pine with grass	-	×	-	-	-	-	-	-	-	-	-	-	-
T – Sagebrush	-	×	-	-	-	-	-	-	2nd	-	-	-	-
N – Sawgrass	-	-	×	-	3rd	2nd	-	-	-	-	-	-	-
B – Mature brush (1.8 m)	-	-	-	×	-	-	-	-	-	-	-	-	-
O - High pocosin	-	-	-	×	-	-	-	-	-	-	-	-	-
F - Inter. brush	-	-	-	-	2nd	×	-	-	-	-	-	-	-
Q - Alaska black spruce	-	-	-	-	-	×	2nd	-	-	-	-	-	-
D Southern rough	-	-	-	-	-	2nd	×	-	-	-	-	-	-
H – Short needle closed normal dead	-	-	-	-	-	-	-	×	-	-	-	-	-
R – Hardwood litter (summer)	-	-	-	-	-	-	-	×	-	-	-	-	-
U - Western long-needle pine	-	-	-	-	-	-	-	-	×	-	-	-	-
P - South long-needle pine	-	-	-	-	-	-	-	-	×	-	-	-	-
E – Hardwood litter (fall)	-	-	-	-	-	-	-	-	×	-	-	-	-
G - Short-needle closed heavy dead	-	-	-	-	-	-	-	-	-	×	-	-	-
K - Light slash	-	-	-	-	-	-	-	-	-	-	×	-	-
J – Medium slash	-	-	-	-	-	-	-	-	-	-	-	×	-
I - Heavy slash	-	-	-	-	-	-	-	-	-	-	-	-	×

Fire behavior differences among these four groups are basically related to fuel load and its distribution among fuel particle size classes. Fuel models are described by fuel load and the ratio of surface area to volume for each size class; the depth of fuel bed involved in fire front; and fuel moisture and/or moisture of

extinction (See Table 3). Another new program FARSITE (Finney 1995, 1998) is used to simulate fire growth across landscape through variable fuels and terrains under changing weather conditions based on fire models of BEHAVE.

Table 3. Fuel models used in the National Fire Danger Rating System (Andrews 1986)
Available at: http://www.npwrc.usgs.gov/resource/habitat/behave/table1.htm.

Fuel model	Typical complex	Fuel loading (t/ha)				Fuel bed depth (cm)	Moisture of extinction dead fuels(%)
		1 hr	10 hr	100 hr	Live		
Grass and grass-dominated							
1	Short (30 cm) grass	0.74	-	-	-	1.0	12
2	Timber	2.00	1.00	0.50	0.50	1.0	15
3	Tall (76 cm) grass	3.01	--	-	-	2.5	25
Chaparral and shrub fields							
4	Chaparral (1.8 m)	5.01	4.01	2.00	5.01	6.0	20
5	Brush (61 cm)	1.00	0.50	-	2.00	2.0	20
6	Dormant brush hardwood slash	1.50	2.50	2.00	-	2.5	25
7	Southern rough	1.13	1.87	1.50	0.37	2.5	40
Timber litter							
8	Closed timber litter	1.50	1.00	2.50	-	.2	30
9	Hardwood litter	2.92	0.41	0.15	-	.2	25
10	Timber (litter and understory)	3.01	2.00	5.01	2.00	1.0	25
Slash							
11	Light logging slash	1.50	4.51	5.51	-	1.0	15
12	Medium logging slash	4.01	14.03	16.53	-	2.3	20
13	Heavy logging slash	7.01	23.04	28.05	-	3.0	25

Fuel classification in Greece (Promethus system)

Within Greece, the system referred to as "PROMETHEUS" deals with the composition and the sorting of various types of vegetation within the ecosystems of Greek forests. According to this system, fuels are divided into 7 types (Giakoumakis 2002). The various types of forest fuels are as follows:

Land Fuel: This category comprises lands consisting of agricultural and herbaceous vegetation. Such fuel is usually thin and dry during the summer period, and consequently fires spread quickly and at a low flame height.

Low-lying Shrubs: This category comprises grasslands, low-lying shrubs (30–60-cm high) and a high percentage (30-40%) of herbs. In this category are also included harvested forest areas in which some residual trees still may exist.

Medium Shrubs: This category comprises medium to large-sized shrubs (0.60–2.0-m high). Land coverage can be greater than 50%. Areas of natural or artificial regeneration can also be included in this type.

Tall Shrubs: This category comprises tall shrubs (>2.0-m high) and areas consisting of young tree plantations, resulting from regeneration efforts.

Forest areas with no understory: This category comprises areas where undergrowth has purposely been removed, either by mechanical or chemical methods. In this category, fires are usually slow spreading.

Forest areas with medium understory: This category comprises forests where the tree crown is much higher than the uppermost parts of the understory vegetation (i.e., there is a break between the fuels found in the understory and the crown). The understory usually consists of low-lying shrubs. Fires characteristic of this category are usually low intensity, which can sometimes develop

to much higher-intensity fires under extreme climate conditions.

Forest areas with high and dense understory: This category comprises forests with high and dense understory growth where there is little separation between the tree crowns and the understory (i.e., continuous fuels). The understory fuels act as ladder fuels to allow the fire to crown in this fuel type, which favors severe and high-intensity fires.

Fuel types in Australia

Fire danger rating systems were developed for application right across Australia for three distinct fuel types: open grasslands, dry eucalyptus forests and heath/shrublands. The forecasting of fire danger ratings is kept separate from the predictions of fire spread and fire behavior in these fuel types (Cheney 1992). The forest fire danger meter and grassland fire danger meter are used in Australia to predict fire danger and fire behavior. The McArthur Forest Fire Danger Meter (http://www.ffp.csiro.au/nfm/fbm/meters/ffdm.html) was designed for general forecasting purposes and is based on the expected equilibrium behavior of fires burning in high eucalypt [*Eucalyptus sp.*] forest carrying a fine fuel load of 12.5 t·hm^{-2} and traveling over level to undulating topography. (The Grassland Fire Danger Meter (http://www.ffp.csiro.au/nfm/fbm/meters/gfd.html) predicts a fires potential rate of forward spread across continuous grass in gently undulating terrain. Combined with temperature, relative humidity and wind speed, it gives an index of the degree of difficulty of suppressing fire in a standard, average pasture carrying 4 t·hm^{-2} of fuel.

Fuel Models for Switzerland

Harvey *et al.* (1997) adapted the US Forest Service method for developing fuel models for surface fires (Brown et al. 1982, Rothermel 1972) to Swiss conditions. Six fuel models were derived (*Pinus mugo grex arborea* together with *Larix decidua*,

Pinus mugo grex arborea, Pinus mugo grex prostrata, Castanea sativa, frequently burned areas with various fern [*Polypodium*] and broom [*Genista*] species, and cultivated conifer forests) (See Table 4).

Table 4. Fuel Models used in Switzerland (Harvey *et al.* 1997).

Fire Characteristics	Model A P. mugo grex arborea and Larix deciduas	Model B P. mugo grex arborea	Model C P.mugo grex prostrata	Model D Cultivated conifer forests (Ti)	Model E Frequently burned areas with ferns, brooms (Ti)	Model F Castanea sativa (Ti)
Rate of spread (m/s)	0.00260	0.00652	0.00379	0.0043	0.0245	0.0078
Flame length (m)	0.2482	0.6911	0.5582	0.3542	0.8963	0.3692
Fireline intensity (kW/m)	22.39	168.84	145.90	27.22	204.75	29.77
Flame zone (m)	0.0284	0.0874	0.0593	0.0462	0.1772	0.0577
Heat release (kJ/m^3)	5710	19709	20483	6192	8323	3801
Reaction intensity (kW/m^2)	477	1407	1305	589	1155	516

Methods for fuel mapping

Four approaches for mapping fuels have been found to be acceptable: (1) field reconnaissance; (2) direct mapping; (3) indirect mapping; and (4) gradient modeling (Keane 2001). The temporal documentation of fuel conditions requires enormous field survey efforts to keep fuel-type maps current, thus constraining their operational usefulness if not kept updated. Satellite remote-sensing techniques provide an alternative source for obtaining fuel data, since they provide cost-efficient, comprehensive spatial coverage and enough temporal resolution to update fuel maps in a more efficient and timely manner than traditional aerial photography (Oswald *et al.* 1999) or field survey. Additionally, satellite sensors provide digital information that can easily be tied into other spatial databases using GIS analysis, which can be quickly imported into running fire behavior and growth models.

The use of remote sensing in creating fuel maps is an extremely difficult and complex process, as it requires expertise in image classification, fire behavior, fuel modeling, fire ecology, and GIS analysis. However, the use of remote-sensing data for classifying and mapping vegetation is becoming the primary and preferred method for assessing fuels. Fuel maps for use in the Canadian FBP System were derived from a satellite image-based land-cover classification of Canada. The satellite imagery was acquired between 1988 and 1991 by the Advanced Very High Resolution Radiometer (AVHRR) sensor on the National Oceanic and Atmospheric Administration (NOAA) satellite series and was processed to produce a composite image representative of the summer burning months. Unfortunately, the land-cover classification did not distinguish between different coniferous forest species. The coniferous cover was either classified as C-1 or C-2, depending on tree density (i.e., there was no mention of the other confer types C3 to C-7). Shrubs were classified as D-1, and croplands as O-1. Therefore, this fuel map (http://cwfis.cfs.nrcan.gc.ca/en/background/bi_FBP_dsm_e.php) gives only a general idea of the fuel types present and is not necessarily detailed enough for daily operational use by fire management agencies. European fuel-type maps only exist at a national level yet do not allow any intercomparison of types be-

cause of lack of homogeneity in the classification of the fuel types between countries (Sebastián-López *et al.* 2002). For this reason a pan-European fuel-type map was derived as a model input. A fuel-type map was developed through the intersection of the CORINE Land Cover (CLC) and the "Natural Vegetation Map of Europe" (Sebastián-López *et al.* 2000). The intersection of CLC classes with the vegetation map resulted in smaller homogeneous regions of similar fuel types, where a particular fuel type was assigned to each region. The assignment process was carried out with the help of the NFDRS fuel model key (Deeming *et al.* 1978), which classifies the fuels according to the type of understory vegetation (mosses, marshes, grasses, brushes, or trees) that would carry a fire once ignited and its structural characteristics.

A well-accepted class system, which takes into consideration the specific characteristics of the area under investigation, is also necessary (Loveland 2001). Supervised classification is the most commonly used method in remote sensing for identification of spectrally similar objects on an image (Jensen 1986). Data for classification can come from satellite images, aerial-photography, and field measurements. In the past, most of the techniques that have employed aerial photography or satellite imagery have been based on differences within spectral information. However, there is still the need to find an appropriate and accurate method for fuel-type mapping (Wagtendonk, 1997). Giakoumakis *et al.* (2002) used a method referred to as object oriented classification method to make fuel maps with a more satisfactory result Two Object-Oriented Models for fuel type mapping based on the PROMITHEUS fuel type classification system were created; one for LANDSAT TM and one for IKONOS. LANDSAT provides enough information to be able to recognize the main classes (water, bare land, shrubs and forest) and the subclasses (coniferous, broad leaved trees etc). And IKONOS can provide us with the information necessary to recognize individual objects, detect texture differences among them, and irregularities in the areas under investigation. This method adopts not only the spectral signature methodology but also some spatial characteristics – such as shape, texture and neighboring objects – were taken as the main classification factors. Kwasny (2000) used Landsat 7 Thematic Mapper (TM) images (30-m pixel resolution) and some high-resolution imagery (1-m pixel resolution) to map vegetation

in green swamp preserve for fuel modeling purposes. The results were used for data input into the FARSITE fire growth model which aids fire managers in predicting the intensity and extent of a prescribed burn (Finney *et al.* 1994). Dymond *et al.* (2004) developed a template of fuel characteristics from temperate fuel classification systems and gathered data from the field and a literature search. The result was eight fuel types and two soil modifiers, which characterized fire occurrence and fire behaviour.

More common has been the generation of fuel maps on small regional scales from remote-sensing images based on the analysis of medium- to high-resolution 30–0.61-m sensors, such as Landsat MSS and Landsat TM data (Agee and Pickford 1985; Castro and Chuvieco 1998). Landsat characteristics represent a good compromise between spectral and temporal resolutions with an adequate spatial coverage for normal operational fire management applications (Riaño *et al.* 2002). Fuel-type maps were derived from Landsat TM satellite images and digital elevation data (DEM). DEM was used to calibrate the satellite images and confirm the tree's distribution as an important index. The main problem in discriminating amongst fuel types is differentiating vegetation heights and understory vegetation composition. An estimation of canopy height could be used to help identify some fuel types. SPOT-HRV has been used to estimate heights using empirical approaches (Wulf *et al.* 1990). New sensors, such as hyperspectral and radar have been also tested for this application. For instance, the Airborne Visible/Infrared Imaging Spectrometer imager (with 224 bands) has been used for the spectral characterization of fuel types (Roberts *et al.* 1997). While sensors of this type have great potential for mapping vegetation properties because of their high spectral resolution, they have been limited by the reduced spatial coverage they provide. New satellite hyperspectral sensors, such as Hyperion (http://eo1.gsfc.nasa.gov) and Moderate Resolution Imaging Spectroradiometer (MODIS) (http://modis.gsfc.nasa.gov) may change this situation.

Traditional approaches for mapping fuel types have been to analyze aircraft and Landsat MSS data collections. For example, single-scene Landsat TM images have been used in the past to classify fuels (Toot and van Wagtendonk 1999). Maps produced from that analysis have been used to predict the behavior of two large wildland fires that were being allowed to burn to meet resource objectives, plan for extensive prescribed fires set by managers, and to make tactical decisions on a wildland fire that was being actively suppressed. In each case, operations were enhanced by the availability of accurate information on fuels. In order to enhance the single-scene map, Wagtendonk & Root (2000) used multi-temporal Landsat TM imagery for developing a technique to identify fuel types based on seasonal changes in plant phenology. Such an analysis techniques would allow them to discriminate fuels based on both spectral and temporal characteristics.

Other efforts have concentrated on low-spatial resolution sensors, such as the NOAA AVHRR images (Zhu and Evans 1994). The main advantage of this sensor is the multi-temporal database made possible by it's high temporal coverage. This is very useful for characterizing the fuel types at regional and global scales. However, the low spatial resolution of this sensor (1 km at nadir) limits its suitability at a stand level. The classification accuracy of fuel-type discrimination may be rather low when the fuel beds or land-use patterns are very complex.

Conclusion and Discussion

The knowledge of natural fuel loads (biomass weights) and species composition is critical for improving current fire prevention and fire behavior modeling, which can alleviate the negative impacts of fire on the ecosystem. Fuel-type maps are essential for computing fire hazard spatially and for assessing fire risk by their use in models simulating fire growth and intensity across a landscape (Keane *et al.* 2001). Fuel-type maps account for structural characteristics of vegetation related to fire behavior and fire propagation. The fire behavior characteristics of individual vegetation species are not necessarily relevant to fire management since the very same species may present completely different fire propagation rates if their fuel loads, densities, vertical continuity, compactness, or surface area to volume ratio characteristics are different dependent upon maturity.

Fuel type is one of the most important factors that should be taken into consideration for fire planning. Development of fuel models becomes an important input for software that are being used to predict fire danger and fire behavior. Remote-sensing data is becoming the primary method in fuel classification and mapping efforts. Satellite sensors provide digital information that can easily be tied into other spatial databases using GIS analysis, which can be imported into fire behavior and growth models.

The ongoing development of sophisticated fire behavior, fire effects, and carbon balance models globally and the implementation of large landscape assessments have demonstrated the need for a comprehensive system of fuel classification that more accurately captures the structural complexity and geographical diversity of fuelbeds. There is a need to look at fire-fuels mapping from a broader perspective (that is, beyond mapping vegetation to fit into the traditional fuel model schemes) that lends itself more effectively to state-of-the-art remote-sensing capabilities.

Presently, China has never developed a national fire danger rating system. Without this,fire behavior prediction and fire effect models have not been developed either. Even a simple fuel map of China cannot be found that could be used by its fire agencies. Fire-management issues, corresponding to different phases of a fire cycle, require different but related research approaches and technologies. For example, fuel reduction requires mapping of the spatial distribution of vegetation characteristics and fuel models, whereas the monitoring and forecasting of fire-ignition danger primarily depends upon coarse-resolution satellite data and weather models. In addition, the use of accurate fuel models will make fire-danger forecasting more consistent and accurate. There is an urgent need for more mapped information on wildland fuels, particularly those in or near the urban interface, to be used in current fire-behavior models (van Wagtendonk *et al.* 2004). Knowing the amount of biomass and other fuel characteristics across a landscape is becoming increasingly important to fire managers as new generation fuel and fire management decision support systems come on line. Given the development of fire management systems elsewhere in the world, we suggest that China should make initial efforts to develop fuel types and models relevant to its fires followed by development of a national fire danger rating system to improve the current poor fire management situation. With accurate fuels information, fire managers should be able to make better-informed decisions about ongoing wildland fires and fuels treatments. These deci-

sions will result in safer conditions for fire fighters and less re-
source damage. Based on this initial work, development of fire
behavior models on stand scale and landscape scale could be
realized.

References

Agee, J.K. and Pickford, S.G. 1985. Vegetation and Fuel Mapping of North
Cascades National Park Service Complex [R]. National Park Serv., Coop-
erative Park Studies Unit, Univ. Washington, Seattle, WA.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire
behavior [R]. USDA For. Serv., National Wildfire Coordinating Group,
Gen. Tech. Rep. INT-122.

Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling
system [R]. Burn subsystem. Part 1. USDA For. Serv., Gen. Tech. Rep.
INT-194.

Brown, J.K. 1982. Fuel and fire behavior prediction in big sagebrush [R].
USDA For. Ser., Res. Pap. INT-290.

Byram, G.M. 1959. Combustion of forest fuels [C]. In: K.P. Davis (ed.), Forest
Fire: Control and Use. New York: McGraw-Hill, 61-89.

Canadian Forestry Service. 1987. Tables for the Canadian Forest Fire Weather
Index System [R]. Can. For. Serv., For. Tech. Rep. No. 25 (4th edition). Ot-
tawa, ON.

Canadian Interagency Forest Fire Centre. 2002. The 2002 glossary of forest
fire   management   terms.   Available   at
http://wlapwww.gov.bc.ca/esd/fire_mgmt_gloss_2002.pdf.

Castro, R., and Chuvieco, E. 1998. Modeling forest fire danger from geo-
graphic information systems [J]. Geocarto Int., 13: 15-23.

Cheney P. 1992. A National Fire Danger Rating System for Australia. Interna-
tional Forest Fire News, (No. 6 - January 1992)[OL]. Available at:
http://www.fire.uni-freiburg.de/iffn/ country/au/au_4.htm.

De Wulf, R.R, Goossens, R.E., Roover, B.P., and Borry, F.C. 1990. Extraction
of forest stand parameters from panchromatic and multispectral SPOT-1
data [J]. Int. J. Remote Sens., 11: 1571-1588.

Deeming, J.E., Burgan, R.E., and Cohen J.D. 1978. The national fire-danger
rating system – 1978 [R]. USDA For. Serv., Gen. Tech. Rep. INT-39.

Dymond C.C., Roswintiarti, O., and Brady, M. 2004. Characterizing and
mapping fuels for Malaysia and western Indonesia [J]. Internat. J. of Wildl.
Fire, 13: 323-334.

Food and Agriculture Organization of the United Nations. 1986. Wildland
Fire management terminology [R]. For. Pap. M-99.

Finney, M.A. 1995. FARSITE - A Fire Area Simulator for Mangers [C]. In:
The Biswell Symposium: Fire Issues and Solutions in Urban Interface and
Wildland Ecosystems [R]. USDA For. Serv., Gen. Tech. Rep. PSW-158.

Finney, M.A. 1998. FARSITE: Fire Area Simulator-model development and
evaluation [R]. USDA For. Serv., Res. Pap. RMRS-RP-4.

Forestry Canada Fire Danger Group, 1992. Development and structure of the
Canadian Forest Fire Behavior Prediction System [R]. For. Can., Ottawa,
On. Inf. Rep. ST-X-3.

Giakoumakis, M. N., Gitas, I.Z., and San-Miguel J. 2002. Object-oriented
classification modeling for fuel type mapping in the Mediterranean, using
LANDSAT TM and IKONOS imagery preliminary results. In: Viegas (Ed.)
Forest Fire Research & Wildland Fire Safety. Millpress, Rotterdam, 1-13

Harvey, S., Rüegsegger, M., and Allgöwer, B. 1997. Fuel Models for Swit-
zerland   (Swiss   National   Park)   [OL].   Available   at:
http://www.geo.unizh.ch/gis/research/edmg/fire/papers/minerve/fuel.pdf

Jensen, J.R., Beaty, K.A., Byron, J.R., Huang, X., Jackson, M.W., Yang X.

1986. Introductory Digital Image Processing: A Remote Sensing Perspec-
tive [M]. 2nd edition.. NJ(USA): Prentice Hall PTR, Upper Saddle River,
p384

Keane, R.E., Burgan, R., and Wagtendonk, J.V. 2001. Mapping wildland fuels
for fire management across multiple scales: Integrating remote sensing, GIS,
and biophysical modeling [J]. Internat. J. Wildl. Fire 10: 301–319.

Kwasny, J.L. 2000. Mapping vegetation in green swamp preserve for fuel
modeling using remote sensing techniques [D]. Great Britain: Nicholas
School of the Environment of Duke Univ.,Master's Thesis.

Loveland, T. R. 2001. Toward a national fuels mapping strategy: Lessons
from selected mapping programs [J]. Internat. J. Wildl. Fire 10: 289-299.

National Wildfire Coordinating Group. 1996. Glossary of Wildland Fire Ter-
minology. National Interagency Fire Center, USA [OL]. Available at:
http://www.nwcg.gov/teams/pmo/products/wfglossary/content.htm.

Oswald, B.P., Fancher, J.T., Kulhavy, D.L., and Reeves, H.C. 1999. Classify-
ing fuels with aerial photography in East Texas [J]. Internat. J. Wildl. Fire,
9: 109–113.

Riaño, D., Chuvieco, E., Salas, J., Orueta, A.P., and Bastarrika, A. 2002.
Generation of fuel type maps from Landsat TM images and ancillary data
in Mediterranean ecosystems [J]. Can. J. For. Res., 32: 1301–1315.

Roberts, D.A., Green, R.O., and Adams, J.B. 1997. Temporal and spatial
patterns in vegetation and atmospheric properties from AVIRIS [J]. Remote
Sens. Environ., 62: 223–240.

Root, R.R. and van Wagtendonk J.W. 1999. Hyperspectral analysis of
multi-temporal Landsat TM data for mapping fuels in Yosemite National
Park [C]. In: Portland: Annual Conf. Amer. Soc. Photog. and Remote Sens-
ing.,   OR.   Available   at:
http://www.werc.usgs.gov/yosemite/posters/yosemite-posters.html

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in
wildland fuels [R]. USDA For. Serv., Gen. Tech. Rep. INT-115.

Sebastián-López A., S. Miguel-Ayanz J., Libertà G. 2000. An integrated
forest   fire   risk   index   for   Europe   [OL].   Available   at:
http://natural-hazards.jrc.it/documents/fires/2000-presentations/earsel2000.
pdf.

Sebastián-López, A. and San Miguel-Ayanz, J. 2002. Integration of satellite
sensor data, fuel type maps and meteorological observations for evaluation
of forest fire risk at the pan-European scale [J]. Int. J. Remote Sensing 23:
2713-2719.

Trabaud, L. (ed.). 1999. Life and environment in the Mediterranean [M].
Southampton(France): WIT Press, p 400.

Van Wagtendonk, J.W. 1997. Use of thematic mapper imagery to map fuel
models [C].. In: Proceedings of 13th Conference on Fire and Forest Mete-
orology, Oct 27-31, 1996 in Lorne, AUSTRALIA,.p22–26

Van Wagtendonk, J.W. and Root, R.R. 2000. Hyperspectral analysis of
multi-temporal Landsat TM data for mapping fuels in Yosemite National
Park [C]. In: Neuenschwander, L.F. and K. C. Ryan (Tech. Eds.), Proceed-
ings of the Joint Fire Science Conference and Workshop.. Vol. 1. Boise, ID,
15-17 June, p. 224-228.

Van Wagtendonk, J.W., Zhu, Z., and Lile E.L. 2004. Prefire risk assessment
and fuels mapping [C]. In: Livingston, R. K. (Ed.) Third US Geological
Survey Wildland Fire-Science Workshop.. USGS Scientific Investigations
Report 2004-5005, p 49-52

Zhu, Z. and Evans, D.L. 1994. US forest types and predicted percent forest
cover from AVHRR data [J]. Photogramm. Eng. Remote Sens., 60:
525-531.